Searching for the missing baryons in the Warm-Hot Intergalactic Medium

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At low redshift ($z < 2$), almost half of the baryons in the Universe are not found in bound structures like galaxies and clusters and therefore most likely reside in a Warm-Hot Intergalactic Medium (WHIM), as predicted by simulations. Attempts to detect WHIM filaments at cosmological distances in absorption towards bright background sources have yielded controversial results that I review here. I argue that a secure detection of absorption features by the WHIM is at the limit of the *XMM-Newton* capabilities, but feasible. A proper characterisation of the whole WHIM belongs to the realm of future X-ray missions.

1 Introduction

In the current cosmological paradigm, the content of the Universe is dominated by the "dark sector" (Dark Matter and Dark Energy), with only $\sim 4.5\%$ being in the form of baryonic matter. This distribution is observationally supported by the angular shape of the Cosmic Microwave Background anisotropies and by counts of type Ia Supernoave as a function of redshift. The small fraction of baryons was inferred long ago by Big Bang nucleosynthesis being responsible for the formation of light elements. In particular a higher baryon density early Universe would be unable to produce enough Deuterium (and ^{3}He) to the level required by its measured abundance and a lower baryon density Universe would not generate enough ^{4}He. It is a remarkable success that the value of the baryon density inferred from D/H measurements in the Lyman α forest towards distant QSOs agrees with that derived from the power spectrum of the anisotropies in the CMB, with a value $\sim 4.5\%$ (for a Hubble constant $H_0 = 70\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, a value used throughout this paper).

As noted in a number of works, at redshift $z > 2$ the amount of baryons found in the Universe is roughly consistent with the above estimate (see, e.g., Fukugita, Hogan & Peebles 1998). A significant fraction of them reside in the Lyman α absorption systems, and in particular in the Damped Lyman α Absorbers or DLAs. At lower redshift, it is expected that the amount of baryons contained in these absorbers decreases, as they should be forming stars. The number of absorbers per unit redshift decreases substantially towards lower redshift in such a way that the amount of baryons contained in the Lyman α absorbers is negligible at $z = 0$. However, the baryon density found in stars, inter-stellar and the intra-cluster medium in the local Universe is significantly lower than the 4.5% of baryons contained in the Universe. This has been summarized by Nicastro et al (2005a) with the conclusion that the grand total of detected baryons at $z < 2$ is 2.5%. Therefore this opens a major cosmological issue: 45% of the baryons in the local Universe are missing.

On the other hand, it is theoretically inconceivable that all baryons at low z are locked into stars, galaxies and clusters of galaxies. There are at least two reasons for this: first the efficiency of forming galaxies in binding all baryons is surely not 100%; second, the evolution of stellar populations in galaxies involves Supernovae, winds and other phenomena that will end up polluting and enriching the surrounding intergalactic medium. Using simulations, it has been confirmed in a number of papers (Ostriker & Cen 1996, Cen & Ostriker 1999, Davé et al 1999) that a significant fraction of baryons would reside today in a Warm-Hot Intergalactic Medium (WHIM), with temperatures ranging between 10^5 and 10^7K. Using cosmological simulations, Davé et al. (2001) concluded that this Warm-Hot component of the Intergalactic Medium becomes more abundant towards low redshift, that it becomes hotter with time and that its spatial distribution follows the general Dark Matter filamentary structure. The WHIM is heated to such high temperatures primarily by shocks, as assumed in the above modeling. Extra heating from Supernovae or AGN of the intergalactic baryons has also been invoked by Pen (1999) and Wu, Nulsen & Fabian (2001), in such a way that its thermal emission does not exceed the extragalactic component of the soft X-ray background. The required amount of heat deposited in the WHIM by these non-gravitational processes (of the order of 1 keV per nucleon) will increase the temperature of the intergalactic gas to $\sim 10^7$ K.

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Most of the WHIM gas is contained in non-virialized structures. Detailed simulations of the distribution of various ion species have been performed by Fang, Bryan & Canizares (2002), showing that higher ionisation species tend to appear in higher density environments, but the abundant ions such as OVII or OVIII are to be found in the low-density filaments, and when observed in absorption towards distant X-ray sources might give rise to an "X-ray forest" (Hellsten et al 1998). Velocity broadening in these structures is significant ($\sim 100 \, \mathrm{km \, s^{-1}}$).

In this paper I review some of the attempts conducted during the last few years with the *XMM-Newton* and *Chandra* gratings in attempting to detect WHIM filaments in absorption towards bright background sources. A local WHIM component has been detected and confirmed beyond any doubt. However, the situation regarding non-local WHIM filament detections is not fully settled. Earlier claims of detections of absorption features at significant redshifts were not confirmed later. There is now a heated debate around the detection of a couple of intervening WHIM filaments along the line of sight towards Mrk 421, with unclear outcome. After discussing all this, I will suggest a possible way forward do detect WHIM filaments with contemporary instrumentation.

2 Detecting WHIM filaments

According to simulations, the WHIM filaments potentially detectable are constituted by extremely tenuous gas (density $\sim 10^{-4} - 10^{-6} \, \mathrm{cm^{-3}}$) extending over vast regions of space ($\sim 1 \, \mathrm{Mpc}$). The temperature should exceed $10^5 \mathrm{K}$, otherwise the usual UV absorption lines would be detected, and cannot exceed too much $10^7 \mathrm{K}$ as otherwise the CMB would be significantly Comptonised.

The possibility of detecting the WHIM in emission has been discussed, e.g., by den Herder et al (2004). The intrinsic difficulty in detecting tenuous gas resides in the fact that the emissivity scales with the square of the density. The figure of merit for an extended source is the grasp (effective area times solid angle times exposure time), and as discussed by den Herder et al (2004) this requires a dedicated mission. High spectral resolution across the field of view is essential to fight efficiently the background, which is rich in emission lines. Indeed, detecting the WHIM in emission would yield the most complete picture, as in addition to redshift distribution, physical state of the filaments, chemical abundances etc. it would also yield the spatial distribution itself, i.e., the filamentary structure.

The alternative way of detecting tenuous gas is in absorption towards a bright background source. For a given resonant transition, the equivalent width of the absorption lines scales as the gas density, as opposed to the gas emissivity which scales as the square of the density. Therefore, absorption is in principle an easier way to detect the low density WHIM. The most important requirement then is that a bright enough background source must be found. High resolution spectroscopy (for a point source) is also essential to detect weak absorption features, as the ones expected from tenuous gas. The obvious disadvantage with respect to the detection of emission from the WHIM is that each observation traces only a single line of sight and therefore information on the spatial distribution is in principle lost (or it requires multiple observations along nearby lines of sight).

There is, however, an important additional difference between the gas seen in emission and absorption. Emission dims as the square of the distance and therefore samples preferentially the local WHIM component. The redshift dependence of the absorption equivalent width is very mild (only through the stretching of the wavelength scale, so the dependence with distance is marginal), so in principle higher redshifts can be explored with absorption experiments. The difficulty resides, obviously, in finding bright enough targets at significant cosmological distances.

At the spectral resolution of contemporary instruments like *Chandra*/LETGS or *XMM-Newton*/RGS (with spectral resolution slightly better than $1000 \, \mathrm{km \, s^{-1}}$), most WHIM absorption lines, with a Doppler velocity parameter $b \sim 100 \, \mathrm{km \, s^{-1}}$ will be unresolved. The minimal equivalent width detectable in a properly sampled spectrum, with signal to noise S/N per spectral resolution element (of width $\Delta\lambda$) is of the order of a few $\Delta\lambda(S/N)^{-1/2}$. Experience with UV and optical absorption line spectroscopy towards distant QSOs demonstrates that unless S/N exceeds several tens, the spectrum will be polluted with large numbers of spikes which will make the detection of weak absorption features almost impossible. If that condition can be met, then the minimum detectable equivalent width is a fraction of $\Delta\lambda$.

In practice this means that both spectral resolution and effective area are essential for this exercise. The most important transitions used so far (OVI Kα at 22.02Å, OVII Kα at 21.60Å, OVIII Lyα at 18.97Å) occur at a wavelength around $20 \, \text{Å}$ which we take as a reference. The RGS on board *XMM-Newton* has an effective area of $\sim 50 \, \mathrm{cm^2}$ (in each RGS unit), while the LETGS on *Chandra* has an effective area $\sim 20 \, \mathrm{cm^2}$ at this wavelength. The spectral resolution of both instruments are formally equal $\lambda/\Delta\lambda \sim 300$ in first order spectroscopy at 20Å. However, as discussed thoroughly by Williams et al. (2006a), the RGS line spread function has significant extended wings, which subsequently reduces the sensitivity to weak absorption lines (see fig. 3 in that paper). As a consequence we do not have at the moment an instrument that is optimal for the detection of WHIM features in absorption: while *XMM-Newton* has the capability of collecting the counts, *Chandra* has a better suited spectral resolution.

Despite all this, there has been an important success in the search for the WHIM. Nicastro et al (2002), using *Chandra*/LETGS data towards Pks 2155-304, along with data from *FUSE*, found clear evidence for a local WHIM component. Specifically OVII Kα and NeIX Kα were clearly detected, while OVIII Kα and OVII Kβ were detected at

lower significance. This was accompanied by the FUSE detection of at least two velocity components of OVI Kα. Using *XMM-Newton*/RGS data, Rasmussen et al (2003) confirmed that the detection of the $z = 0$ OVII Kα is ubiquitous among extragalactic lines of sight, with clear detections towards Pks 2155-304, 3C273 and Mrk 421.

The origin of this WHIM component is however still unclear. Given the resolution of the existing X-ray dispersive spectrometers, the velocity and structure of the absorbing clouds cannot be determined with enough accuracy to distinguish between an origin in the interstellar medium, the Galactic halo or an extragalactic origin associated to the Local Group. This has been extensively discussed by Nicastro et al (2002), Nicastro et al (2003) and Williams et al (2006b) among others. The mass implied in this absorbing gas component is clearly dependent on the scale spanned, and in the most extreme case of being associated to the Local Group it could account for all the missing baryons in this structure; if, on the contrary, the $z = 0$ WHIM absorber is associated to the ISM or the Galactic halo, the mass implied would be small. As it has been extensively demonstrated by many years of work on UV/optical QSO absorption lines, and confirmed here, the importance of spectral resolution when trying to assign absorbers to known objects (i.e., galaxies) cannot be overstated.

3 Detecting non-local WHIM

Detecting WHIM absorption beyond the local group and trying to somehow quantify the amount of baryons residing in this phase has been and is still a major target of X-ray spectroscopic studies. Ultimately we are dealing with the fate of almost one of every two baryons present in the Universe, so it is hardly surprising that various groups are devoting a lot of effort to this.

The strategy has been to target the brightest background sources with the dispersive spectrometers on board *XMM-Newton* and *Chandra*. For reference, an X-ray source with a 0.5-2 keV flux of $10^{-11} \, \mathrm{erg \, cm^{-2} \, s^{-1}}$ requires several hundreds of ks to produce a spectrum which has a S/N of a few tens per spectral resolution element, as required if weak absorption lines need to be detected. Of course, the sources need to be at cosmological distances to sample a significant path along the line of sight. Often, the highly variable background sources have been observed when in high state to maximise the S/N.

There have been various tentative detections of WHIM absorption lines at significant redshift (Fang et al 2002, Mathur et al 2003) that turned out not being confirmed by deeper observations (Cagnoni et al 2004, Rasmussen et al 2003).

The most recent and detailed work on this has been conducted on the highly variable Blazar Mrk 421 ($z = 0.03$). Nicastro et al (2005a) and Nicastro et al (2005b) claimed the detection of two WHIM absorption systems towards this line of sight, using ~ 200 ks of *Chandra*/LETGS data, when the source was at its historic maximum. The WHIM filaments were reported at $z = 0.011$ (with detections of OVII and NVII at a combined significance of 3.5σ) and another one at $z = 0.027$ (with detections of OVII, NVII and NVI, at a combined significance of 4.9σ). The excitement that triggered these tentative discoveries was enhanced by the estimates presented by Nicastro et al (2005b) whereby the inferred amount of baryons in the WHIM, should these detections be proven reliable, would be $\Omega_{\mathrm{WHIM}} \sim 2.7^{+3.8}_{-1.9}\%$ for an O/H abundance of 0.1 solar, i.e., the WHIM would contain exactly the amount of missing baryons at low redshift.

The same team tried to confirm later these findings with a stacked *XMM-Newton*/RGS spectrum of the same source, collecting ~ 500 ks of good data. In the paper by Williams et al (2006a) it was concluded that despite the long *XMM-Newton* exposure, the data were not sensitive enough to either confirm or reject the *Chandra* findings. For this team, the main reasons for this lack of sensitivity reside in the large number of narrow instrumental features caused by bad detector columns, the intrinsic line spread function (due to its extended wings) and the presence of fixed pattern noise at 29Å. Williams et al (2006a) found upper limits to absorption features expected from the *Chandra* data around 4mÅ, while 2-3mÅ features were expected.

All this has been severely disputed by Rasmussen et al (2007). This competing team has analyzed a total of 950 ks of RGS data on Mrk 421, with a very careful and highly non-standard processing to isolate many detector spatial and temporal features. In addition, they claim that stacking data from a variable source should not be done, but rather an analysis of the combined data set should be performed. The net result is that Rasmussen et al (2007) do detect features associated with the local WHIM as weak as 2.5 mÅ, and find upper limits to the features expected from the non-local WHIM absorbers detected by *Chandra* at the level of 1.9mÅ (the consistency between LETGS and RGS data has been addressed in detail by Kaastra et al 2006). Rasmussen et al (2007) conclude that *XMM-Newton*/RGS data do not confirm the existence of the two WHIM filaments reported by Nicastro et al (2005a) and Nicastro (2005b). Further, Rasmussen et al (2007) point out that the expected number of absorbers towards Mrk 421 down to the best attainable sensitivity is very small, in addition to the fact, remarked by all groups in this field, that the O/H abundance in the WHIM is unknown and difficult to predict from fundamental cosmological principles.

4 A possible way forward

The discussion presented in the previous section shows that the detection of the WHIM features is at the limit of the capabilities of contemporary X-ray dispersive spectrometers. Whether non-local WHIM filaments have been detected is, to say the least, controversial. Even if *Chandra* or *XMM-Newton* end up detecting one or a few WHIM absorbers, the

Table 1   RGS exposure times and expected number of absorbers

Target	z	t_{exp} (Ms)	N_{abs}
3C 279	0.53	20	2.9
4C 71.07	2.17	14-19	≥ 10(*)
3C 454.3	0.86	16	4.3

(*) The exact number depends on the precise ionisation history of the WHIM.

full characterisation of the WHIM will have to await future missions, such as XEUS[1] which are capable of collecting many more photons at a similar or better resolution that the current X-ray spectrometers.

For the time being, my personal view is that the race to detect the first WHIM absorbers and confirm them should be more success-oriented and targeting the detection of a few of such absorbers - to the best of the current knowledge. I propose to keep in mind three points:

- Conduct a "serendipitous" search, i.e., do not target specific lines of sight with nearby groups or clusters or known high-ionisation absorbers from the UV. Only in this way, and following an eventual detection, we might have a direct idea on how many baryons are contained in the WHIM.
- Go for a "secure" detection, i.e., sample enough line of sight (with one or several targets) to span a long Δz range, in such a way that the number of expected absorbers is of several.
- Metal abundance will always be a caveat, as it is very difficult to reliably predict. All the numbers will scale with the value of O/H.

With all this in mind, I used the Chen et al (2003) predictions for the number of OVII and OVIII absorbers per unit z as a function of minimum detectable equivalent width. I then adopted a conservative 3mÅ limit, which Rasmussen et al (2007) demonstrated that can be achieved in an RGS spectrum that contains 10,000 counts in a 50 mÅ bin (this is formally S/N=100 per resolution element). In terms of $dN/(d\ln(1+z))$, we can expect 4 and 3 OVII and OVIII absorbers respectively, for a 0.1 solar metalicity WHIM.

Table 1 shows the RGS exposure time needed for a few distant targets, at significant z along with the number of expected absorbers. Approximately, 10 Ms of *XMM-Newton* RGS exposure are needed for a source with 1 ROSAT PSPC ct/s. Unfortunately only RGS1 counts can be used, as the region around the detectable Oxygen features in the RGS2 is covered by one of the non-functioning CCDs.

The exposure times are very long, and still carry the uncertainty of the metalicity. But exploring the fate of 50% of the ordinary matter in the Universe is among the most important challenges of contemporary Astrophysics.

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[1] http://www.rssd.esa.int/XEUS

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